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LABORATORY AND NUMERICAL STUDIES OF HEAT EXTRACTION FROM HOT POROUS MEDIA BY MEANS OF SUPERCRITICAL CO_2

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ABSTRACT

The use of CO_2 as a heat-transfer fluid has been proposed as an alternative to water in enhanced geothermal systems (EGS). Numerical simulations have shown that under expected EGS operating conditions, CO_2 would achieve more efficient heat extraction performance compared to water. In a set of laboratory experiments, we have investigated heat extraction by flowing dry supercritical CO_2 through a heated porous medium in a laboratory pressure vessel. We have assembled a laboratory apparatus capable of operating at temperatures up to 200°C, pressures up to 340 bar, and flow rates up to 400 ml/min. The experimental system was designed such that measurements and controls at the boundaries could be readily modeled in TOUGH2. We have implemented a model of the experimental system in TOUGH2 and have obtained reasonable agreement between the laboratory measurements and the predictions of the numerical simulation. By continuing to improve both the experimental apparatus and the numerical model, we hope to document the ability of TOUGH2 to make accurate predictions of CO_2 heat extraction performance, with a focus on the application of CO_2 in EGS.

INTRODUCTION

Geothermal energy is a vast resource that, if efficiently utilized, could satisfy the majority of the base load energy demand in the United States (Tester et al., 2006). Current commercial geothermal electricity production is dependent on a number of factors, including an optimized combination of geological conditions such as presence of hydrothermal fluid, high heat flux, high rock permeability and/or high rock porosity. Enhanced (or Engineered) Geothermal Systems (EGS) are an attempt to exploit geothermal energy in locations where these conditions are not optimal (Tester et al., 2006). Most EGS strategies involve reservoir stimulation to overcome the lack of porosity and/or permeability of the rock using various chemical and physical processes, as well as supplying the needed heat transfer process fluid (e.g., water or CO_2) (Majer et al., 2007).

The novel concept of using supercritical CO_2 (SCCO2) as the working fluid in EGS for both reservoir creation and heat extraction was first proposed by Brown (2000). Subsequent work includes numerical simulations of a five-spot well pattern in a hot dry rock (HDR) system, which estimated an approximately 50% greater heat extraction rate using SCCO2 instead of water given the same operating conditions (Pruess, 2006). The advantages of using CO_2 over water as the process fluid in a closed loop HDR system include (1) the much lower viscosity of CO_2, which means that substantially larger mass flow rates can be achieved for a given pressure drop between injection and production points; (2) the much larger density difference between cold fluid in the injection well and hot fluid in the producer, which means increased buoyancy forces for CO_2, which will reduce or even eliminate pumping requirements; (3) the lower mineral reactivity of dry SCCO2, which would reduce equipment fouling, and reduce the possibility of dissolution and precipitation reactions that could negatively impact the reservoir quality; and (4) the hotter reservoirs, which means that reservoirs could be developed without the silica dissolution problems that are present in water-based systems. As an ancillary benefit, practical operation of a SCCO2 system would result in de facto carbon sequestration due to fluid loss to the surrounding formations (Brown, 2000; Pruess, 2006). In light of the promising results of both thermodynamic and chemical simulations (Pruess and Spycher, 2010; Xu and Pruess, 2010), it is necessary to confirm the theoretical work with practical laboratory and field experiments.

This paper presents the ongoing design, implementation, and results of a laboratory-scale SCCO2-based heat extraction experiment, with the goal of verifying and validating TOUGH2 and the ECO2N module for the tested conditions, and improving the design of an experimental system.

EXPERIMENT DESCRIPTION

Our research consists of two major efforts: the creation of a laboratory-derived data set, and the creation of a well-behaved TOUGH2 model of the physical experiment. Great care has gone into designing the physical experiment, such that the boundary conditions could be accurately implemented in the TOUGH2 model.

Experimental Apparatus

The apparatus consists of a temperature-controlled pressure vessel filled with porous media, through which temperature-controlled fluid could be introduced by means of high-pressure high-flow rate pumps (Figure 1). The fluid flow in the vessel can be operated as either a constant fluid injection rate or in a constant differential pressure mode.
The fluid was delivered by a pair of Quizix C-6000-5K pumps, capable of 5,000psi (345 bar) and 400 ml/min fluid delivery rate. The pumps are capable of precisely controlled continuous and pulse-free flow with a resolution of 27.2 nanoliters. The CO_2 is passed through a chiller before entering the pumps in order to fill the pumps with high-density liquid CO_2. After leaving the pumps, the fluid can be either chilled by a second fluid chiller, or heated, depending on the desired experimental parameters. Before entering the vessel, the CO_2 passes through a Siemens Coriolis style mass flow meter. The meter could also be placed at the outlet and used in conjunction with the pump flow readings to measure fluid accumulation in the vessel.

The pressure vessel is a hollow stainless steel cylinder with an inside diameter of 9.1 cm, outside diameter of 12.7 cm, 50.8 cm distance between the end caps, and a pressure safety rating of 34.5 MPa (345 bar, 5000 psi). Instrumentation access to the interior of the vessel is via three axial passages through one end cap, and one passage through the other. The central passages through the end caps are used as the injection and production ports, and the remaining two passages are used exclusively to pass thermocouples through (see below).

Temperature measurements within the sample were made with 23 stainless-steel clad type-T

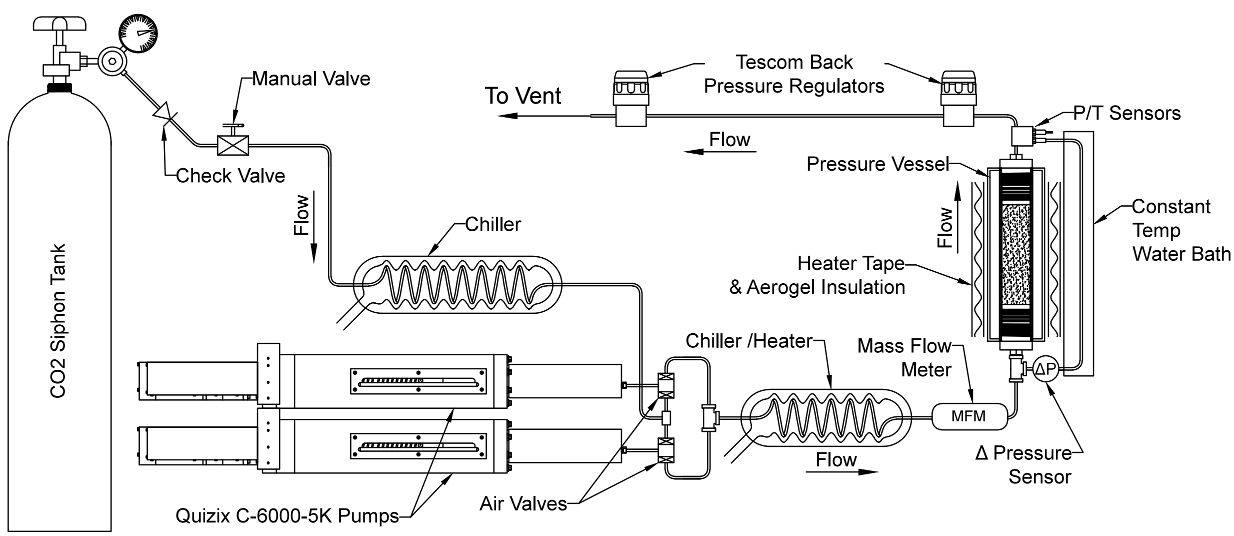

Figure 1. Simplified schematic of the experimental apparatus.

thermocouples, which have a small diameter (0.79 mm) in order to increase the sensor response time and to minimize disturbance to fluid flow. The thermocouples have been arranged at various elevations and radii in the sample, such that each successive vertical level is offset angularly to minimize vertical sensor shadowing (Figure 2).

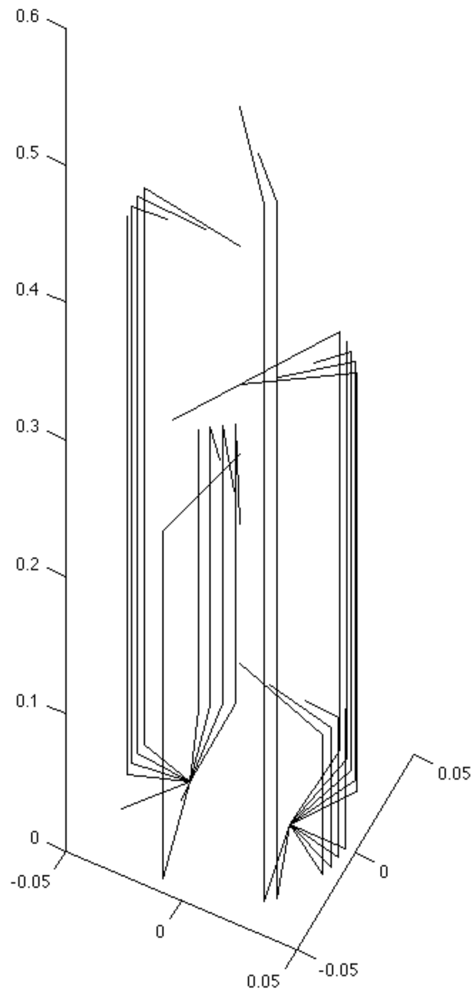

Figure 2. Orthographic diagram of thermocouple placement inside the vessel. Axis units are in meters.

At one elevation in the porous media, two thermocouples were mirrored so that they were both at the same radial distance from the central axis of the vessel. The radially mirrored temperature measurement was designed to test our assumption of radial symmetry in the heat-transfer process.

The injection port of the vessel was lined with a length of nylon tubing through the end cap in order to provide thermal insulation for the injected fluid as it passed through the relatively massive end cap. The injection port was also fitted with a single thermocouple mounted where the injected fluid enters the sample space (not shown in figure).

The sand used in the test sample was prepared from F95 Ottawa silica sand. Sieving and washing resulted in a relatively narrow grain size distribution. The mean grain size falls between 147 and 105 microns with no measurable portion below a grain size of 45 microns. The sand was dry placed in the vessel in multiple lifts, with vibratory compaction between lifts. The vessel was wrapped with heat tape that extended around the exterior of both end caps. Heat-tape thermal output was controlled by either a PID controller using a thermocouple secured on the vessel exterior, or with a pulse-width modulated signal generated by a computer. This allows the vessel boundary to act in either a constant-temperature or a constant-heat-flux mode. Finally, the vessel was wrapped in an aerogel insulation jacket and sealed. The current supplied to the heat tape was monitored using a true RMS current sensor.

The pressure at the outlet of the vessel was controlled by a pair of digital backpressure regulators in series. The fluid exiting the backpressure regulators was vented to the atmosphere. A differential pressure sensor was located at the base of the vessel and connected to the inlet and outlet of the vessel. The tubing that connected the differential pressure sensor to the inlet was encased in a constant-temperature water bath, so that the state of the fluid column in the tube can be determined. It was found in early tests that the small variations in fluid temperature resulted in large variations in fluid density—variations that significantly impacted the differential pressure measurement.

We developed software that incorporates experimental control and data acquisition. All sensor readings were collected by a single Labview-based program that allows for accurate time synchronization of experimental data. The program is capable of controlling the pumps, vessel heat input, and the backpressure regulators. Combining these functions allows for a tightly integrated experimental setup, faster data processing and experimental turnaround time, and less chance of experimental errors.

Experiment Procedure

The tubing and sand-filled vessel were filled with dry CO_2. After heating the vessel to the desired operating temperature, we added or removed anhydrous fluid CO_2 to achieve the desired operating pressure, and the apparatus was allowed to thermally equilibrate. At this point, the backpressure was set to the desired pressure, and cold CO_2 was injected into the bottom of the vessel at a prescribed volumetric flow rate or injection pressure. When the first injection pump approached the end of its cycle, the second injection pump was activated, allowing the first pump to be refilled from the siphon tank. The injection pumps were cycled in this manner until the experimental run was completed.

TOUGH2 Modeling

A 2-D axisymmetric model of the experimental apparatus, which included porous medium, steel vessel, and inlet and outlet material domains, was implemented in TOUGH2/ECO2N. The majority of the modeling work was executed on a dual core 64-bit x86 processor running Apple OSX operating system software. A suite of Matlab scripts was written to allow for automatic generation of the mesh file, input files, and extracting and plotting of the post simulation data. We found that the simulations with TOUGH2/ECO2N were sensitive to cell size, resulting in runs that would produce errors before completion.

The errors appeared to be a result of the small scale of the model. When cells were too small, differences between variables in adjacent cells became too small compared to the machine epsilon (rounding of floating point operations) resulting in errors. The errors occurred at different times in the simulation on different computers that were using different operating systems and CPU architectures. These errors were also found to be dependent on the simulation parameters such as temperature, pressure, and flow rate. The mesh generation script allowed properly sized models to be produced rapidly with a user-selected quantity of cells in each domain axis. When an error was encountered, the number of cells was reduced until the simulation could run to completion.

For example, a simulation run with parameters of 121 bar back pressure, 150 ml/min injection rate, and 75C initial core temperature would fail when the porous medium was modeled with 45 or more horizontal cell layers (cell size height of 11.3 mm). When the number of horizontal cell layers was decreased to 44 (cell height of 11.5 mm) the simulation would run to completion without errors.

PRELIMINARY RESULTS

The temperature data from 22 thermocouples from a representative experimental run is shown in Figure 3. The thermocouples are numbered primarily in order of increasing radii and secondarily by increasing elevation in the vessel. Thermocouple 1, for example, is located on the central axis at the bottom of the vessel, while Thermocouple 22 is located near the vessel wall, at the top of the vessel.

It can be seen from the plot that there is an initial temperature gradient present in the saturated medium with a lower temperature at the base. This gradient is most likely driven by some heat loss to the environment. The numerical model did not develop a similar gradient until a heat sink was included on the vessel exterior.

The temperature front can be seen in the plot as it passes axially through the sample past the measurement locations. After the initial sharp temperature drop, the temperatures gradually approach equilibrium, and a radial temperature gradient then develops, indicated by the grouped lines spreading out. The exterior locations trend towards a higher temperature than locations that are more central (solid lines).

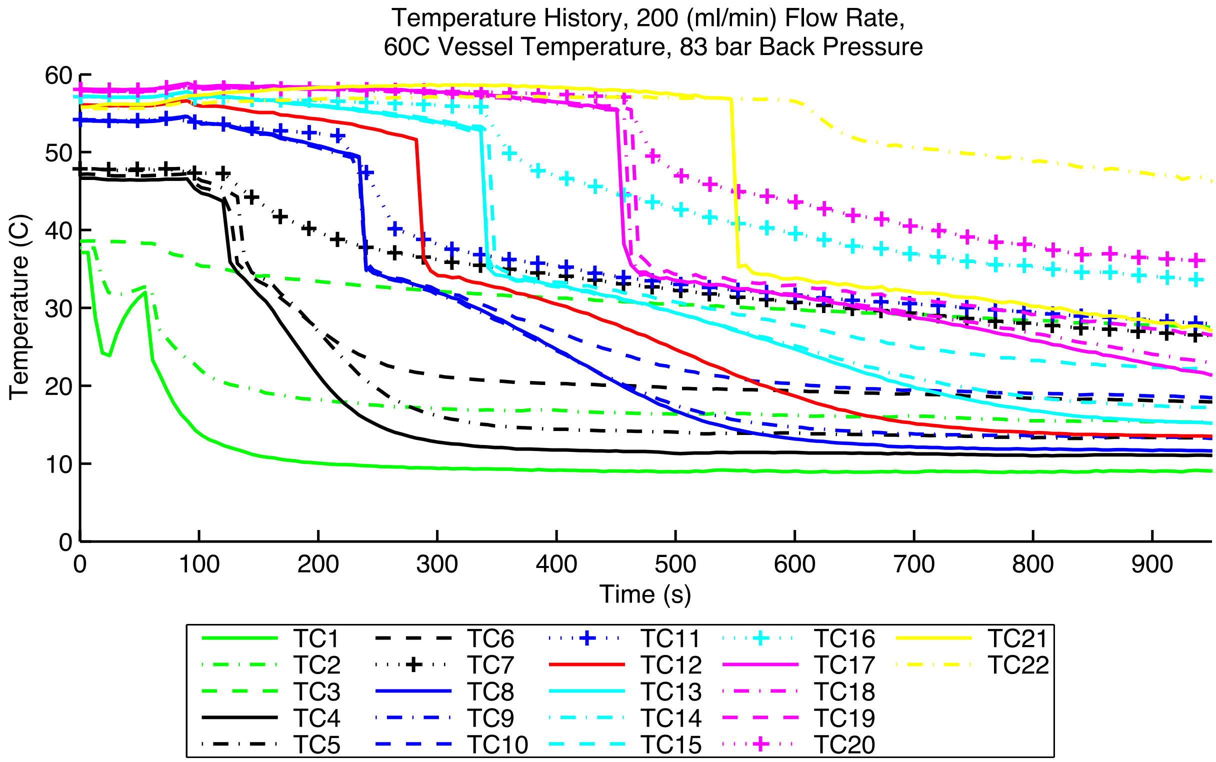

Figure 3. Temperature vs. time data for 22 thermocouples from a representative experimental run.

The interplay between convective and conductive transport can be seen in the shape of the temperature versus time curves. A purely convective process would feature sharp thermal fronts and a near-vertical slope at the time when the cold fluid slug reached the thermocouple. A purely conductive process would generate a gentler slope with smooth transitions. The experimental run shown in Figure 3 was at a relatively high flow rate, and the steep temperature front indicates a convectively dominated behavior. Figure 4 shows temperature data from a lower-flow-rate experimental run that was less convectively dominated (only temperature data from the central axis of the vessel are shown for clarity).

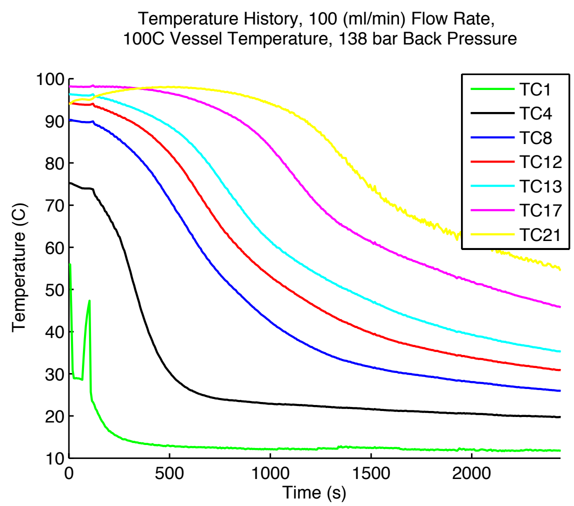

Figure 4. Temperature vs. time from experimental run with a CO_2 flow rate of 100 ml/min.

Modeling results were compared to runs made with an earlier version of the apparatus and generally agreed well (Magliocco et al., 2011). In order to reduce the differences between the modeling results and the experimental results, we made several control and measurement improvements to our apparatus. In our previous experimental setup, we found it difficult to measure the state of the fluid in the fluid delivery pumps, which made it difficult to estimate the mass flow rate of the fluid entering the system. We added a mass flow sensor to our inlet in order to directly measure the mass flow rate regardless of fluid state. We have also added the capability of controlling the exterior of the vessel as a constant heat flux boundary by using pulse-width modulation of the heater current.

Combined with the more efficient insulation provided by the aerogel jacket, the thermal boundary condition at the vessel exterior is much more certain. These hardware improvements will allow us to model the experiment in TOUGH2 more easily and accurately.

FUTURE WORK

We are working on expanding our experimental data set to cover more pressures, temperatures, flow rates, and fluid mixtures (CO_2, water, NaCl brine). Concurrently, we are improving the TOUGH2 model to more accurately reproduce the boundary and initial conditions found in the lab.

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